PRODUCTION OF NB/CU SPUTTERED SUPERCONDUCTING CAVITIES FOR LHC

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Abstract

For the Large Hadron Collider (LHC) at CERN, 21 superconducting 400 MHz single cell cavities have been produced by ACCEL using the technology of coating niobium on copper cavities. This technology was developed by CERN and transferred to industry within the scope of the LEP 200 project. The guaranteed values for the gradient and unloaded quality factor at a bath temperature of 4.5 K are E_{acc} = 5 MV/m and Q_0(5 MV/m) = $2{\cdot}10^9$. The cavities have been tested in a vertical test stand at CERN. All cavities exceeded the guaranteed values, the best quality factor at 5 MV/m was $2.6{\cdot}10^9$. During the vertical test gradients up to 10.5 MV/m were observed with $Q_0 > 10^9$ at 4.5 K. At a bath temperature of 2.5 K gradients up to 14.5 MV/m with $Q_0 > 2.5{\cdot}10^9$ have been reached.

For future applications such as high intensity proton linear accelerators, superconducting cavities designed for acceleration of particles with a velocity in the β range between 0.4 and 0.9 are desirable ($\beta = v/c$, v = velocity of particle, c = speed of light). ACCEL has produced two single cell $\beta = 0.8$ cavities in a collaboration with Mitsubishi Electric Corporation (MELCO). The performance of this cavities is already close to the theoretical values. Further improvement can be accomplished by iteratively optimizing the coating parameters in the next step of R&D phase.

1 INTRODUCTION

In the Large Hadron Collider at CERN a proton current of 560 mA needs to be accelerated from 0.45 TeV to 7 TeV. Superconducting cavities have two major advantages making them the ideal choice for this machine [1], [2]:

- High stored energy which minimizes the effects of periodic transient beam loading.
- High accelerating gradient leading to a small contribution of the machine impedance.

Single cell superconducting cavities with large beam tubes very similar to those designed for high current e^+e^- factories were chosen by CERN. Per beam eight single cell cavities placed in two cryostats are foreseen each cavity delivering a voltage of 2 MV. Four cavities are placed in one common cryostat, so that two cryostats are necessary for each beam. At the cavity beam tubes, there are seven ports available, one port for the main input coupler, two ports for pick-up antennas and four ports for higher order modes (HOM) antennas (see Fig. 1). Important design parameters of the LHC cavities are listed in table 1.

Table 1: Important design parameters of the LHC 400 MHz single cell cavity [3]

$R/Q = V_{acc}^2/(P_{diss}{\cdot}Q_0)$	89 Ω
V_{acc}	2 MV
E_{acc}	5.33 MV/m
Active length	0.375 m
Beam pipe diameter	300 mm
Equator diameter	689 mm
Tuning range	10 kHz
Input coupler power, steady state	116 kW
Input coupler power, peak	176 kW

2 PRODUCTION AND PREPARATION

The cavity is made out of OFHC copper. All parts were electropolished at ACCEL during which a 120 µm thick surface layer was removed. The parts were then electron beam welded. The weld of the equator is realized from the inside with an ”internal EB-gun”. The completed cavity was then chemically prepared. The so called SUBU5 chemistry developed at CERN was used. After careful rinsing with deionized water, the cavity is allowed to dry in a class 100 clean room and ready for magnetron sputtering of niobium. A layer of 1-2 µm niobium is sputtered on the inner surface. The next preparation step is the mounting of the flanges in a class 100 cleanroom. After this mounting procedure, the cavity is again rinsed carefully with deionized water. The cavity is then ready for a cold RF test at CERN. Fig. 1 shows a LHC single cell 400 MHz cavity ready for magnetron sputtering at ACCEL.

3 LHC CAVITY VERTICAL TEST RESULTS

All produced cavities have reached the guaranteed values of E_{acc} = 5 MV/m and $Q_0 = 2{\cdot}10^9$ at a bath temperature of 4.5 K. The distribution of achieved quality factors Q_0 at the accelerating gradient of E_{acc} = 5 MV/m is shown in Fig. 2. Out of the 21 prepared cavities 18 reached this required performance with the first coating. Considering that cavity A17 (see Fig. 2) was coated the first time with a new Nb-cathode with expected lower performance an overall success rate above 90 % has been achieved. Among the 3 cavities (A04, A09, A17) with lower performance, cavity A04 and cavity A17 reached already values close to $2{\cdot}10^9$. The niobium layer of this 3 cavities was stripped off, the coating was repeated and the cavities reached the design parameters with this second coating.

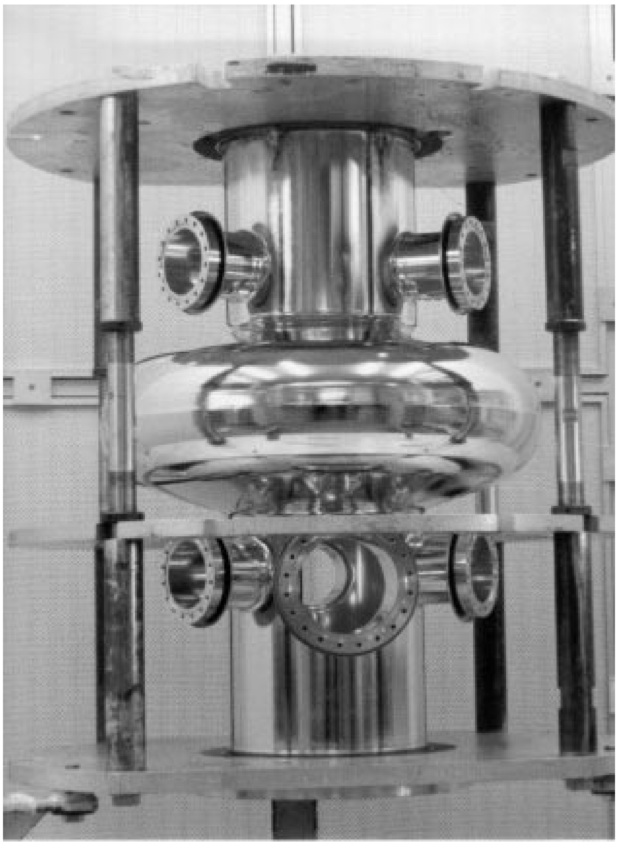

Figure 1: LHC 400 MHz copper cavity ready for magnetron sputtering of niobium. This technology was transfereed from CERN to ACCEL in the scope of the LEP 200 project

The cavities have been tested at CERN at bath temperatures of 4.5 K and 2.5 K. The highest gradient achieved at 4.5 K was 10.5 MV/m with a quality factor of $1.2{\cdot}10^9$. At a bath temperature of 2.5 K the highest achieved gradient was even 14.5 MV/m with a quality factor Q_0 still above $2{\cdot}10^9$. The distribution of all achieved gradients and quality factors at this highest gradients for the two bath temperatures of 2.5 K and 4.5 K is shown in Fig. 3. On the average at 4.5 K a gradient of 9.2 ± 0.6 MV/m and at 2.5 K a gradient of 11.5 ± 1.5 MV/m could be reached. In all cases the gradient was limited by RF power. The average value of the resonant frequency measured at 4.5 K was 400.77 ± 0.19 MHz.

A typical excitation curve (quality factor Q_0 in dependence of the accelerating gradient E_{acc}) is shown in Fig. 4.

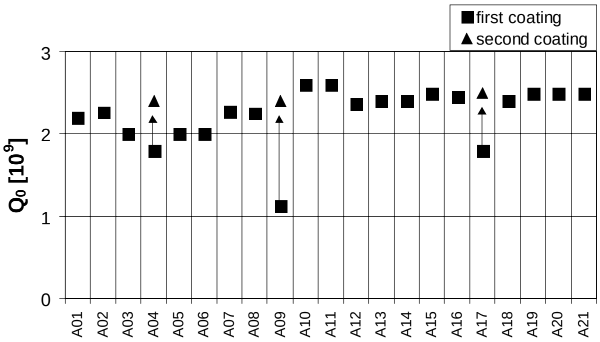

Figure 2: Distribution of cavity quality Q_0 at a gradient of E_{acc} = 5 MV/m and a bath temperature of 4.5 K. 18 cavities reached $Q_0 > 2{\cdot}10^9$ already after the first coating of niobium on copper. For the remaining 3 cavities the 1-2 μm niobium layer had to be stripped off, and the coating had to be repeated

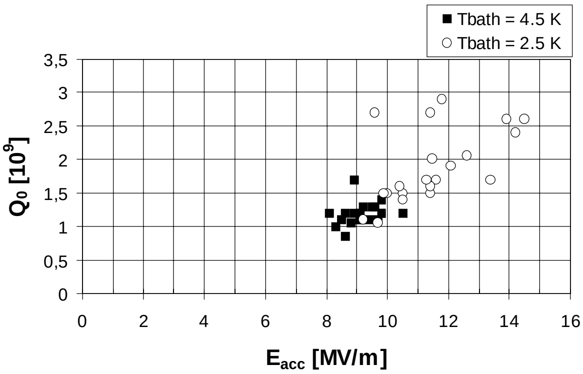

Figure 3: Highest gradients E_{acc} and quality factors Q_0 at the highest gradients achieved at bath temperatures of 4.5 K and 2.5 K in the LHC 400 MHz single cell cavities. The tests were carried out at CERN. The preparation of the cavities prior vertical test was done at ACCEL.

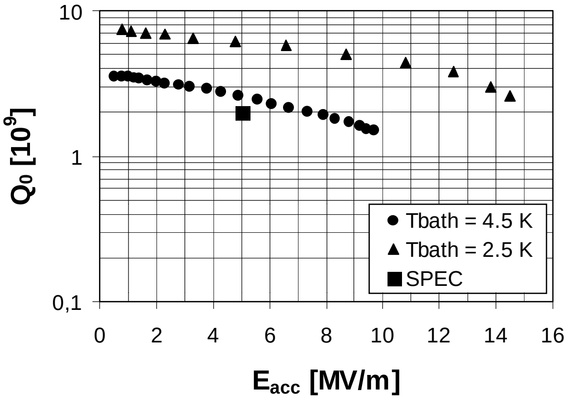

Fig. 4: Performance of cavity A11 at 2.5 K and 4.5 K bath temperature.

4 FUTURE PROJECTS

For high intensity proton linear accelerators superconducting cavities are of high interest, because they can deliver high voltage to the beam and therefore the total length of the linac can be reduced. A second benefit comes from the low power consumption of the superconducting cavities. Therefore lower wall plug power is required. In overall the superconducting choice has the potential to reduce the investment and the operation cost. As protons have a 1836 times higher mass as electrons cavities are required which are optimized for a β-value of the protons in the range of 0.4 < β < 0.9.

4.1 Superconducting 600 MHz low β cavities

In a collaboration with Mitsubishi Electric Company (MELCO) two superconducting prototype single cell 600 MHz Nb/Cu sputtered superconducting cavities were produced at ACCEL optimized for a particle with β = 0.8. The production of the copper cavities was similar to the production of the LHC cavities. The magnetron sputtering of the 1-2 µm niobium was applied with some modifications due to the different geometry of the cavity shape. The detailed sputter parameters were discussed in a close collaboration with CERN. The parameters of the cavities are listed in Table 2.

Table 2: Design Parameters for the prototype β = 0.8 single cell cavities

$R/Q = V_{acc}{}^2/(P_{diss} \cdot Q_0)$	69.6 Ω
G	216 Ω
Active length	0.2 m
Beam pipe diameter	150 mm
Equator diameter	445.8 mm
Fundamental mode frequency	600 MHz
E_{peak}/E_{acc}	2.276
B_{peak}/E_{acc} [mT/(MV/m)]	5.11

Compared to a β=1 cavity, the shunt impedance and the geometric factor G are reduced, and the ratio of peak electric field on the metal surface to accelerating gradient E_{peak}/E_{acc} as well as the ratio of peak magnetic field on the metal surface to accelerating gradient B_{peak}/E_{acc} is enhanced.

4.2 Vertical test results on the β = 0.8 Nb/Cu superconducting cavities

After production and preparation carried out at ACCEL, the β = 0.8 cavities were cold RF tested at CERN and in the JAERI facility by MELCO and JAERI. A typical test result is shown in Fig. 5.

From the BCS theory of superconductivity one can estimate for sputtered niobium a RF surface resistance of approximately 100 nΩ at 600 MHz and 4.5 K. This would correspond to a Q_0 value of about $2 \cdot 10^9$ of the cavity. A value of $1 \cdot 10^9$ has been achieved at low gradients (see Fig. 5). At the maximum accelerating gradient of 7.5 MV/m the quality factor Q_0 was $3.5 \cdot 10^8$. At lower bath temperatures, the Q_0 does not improve much, indicating that the residual resistance of the cavity is in the range of 100 nΩ. In order to reduce both, the continuous slope in the $Q_0(E_{acc})$-curve and the residual resistance, the coating parameters for low β cavities have to be optimized in a next R&D step.

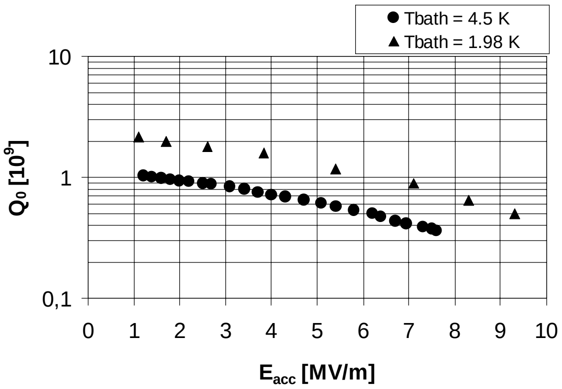

Figure 5: Vertical test result of a 600 MHz β=0.8 cavity at different bath temperatures.

5 CONCLUSIONS

All 21 superconducting LHC 400 MHz single cell cavities fabricated and prepared at ACCEL for a vertical test at CERN exceeded by far the design values of E_{acc} = 5 MV/m and $Q_0 = 2 \cdot 10^9$. The fact that 90 % of the cavities reached this values already after the first coating (and preparation) indicates, that the technique of sputtering niobium on copper cavities can be applied routinely at ACCEL. The good performance of the LHC production and the first results of the low β cavities shows that the technique of sputtering niobium on copper cavities can be used for applications such as high intensity proton linacs.

6 REFERENCES

[1] D. Boussard, E. Chiaveri, E. Haebel, H.P. Kindermann, ”THE LHC SUPERCONDUCTING CAVITIES”, PAC99 (1999)

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[3] ”THE LARGE HADRON COLLIDER – CONCEPTUAL DESIGN REPORT”, CERN/AC/95-05 LHC